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ELECTRONICS RESEARCH LABORATORY

Electronic Warfare Division

RESEARCH REPORT
ERL-0549-RR

A LASER ECM AND ESM FACILITY

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ABSTRACT (U)

This Research Report discusses a Laser ECM/ESM Facility, which was developed to conduct electronic countermeasure and electronic support measure investigations of electro-optic systems. Detailed attention has been drawn to atmospheric effects within the system, and criteria are discussed which are employed to evaluate conditions where such effects become significant.

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1 INTRODUCTION

A laser ECM (Electronic Countermeasure) and ESM (Electronic Support Measure) facility has been developed to investigate the effects of continuous wave (CW) and modulated laser radiation on a number of electro-optic (EO) devices operating in the short waveband of the infrared spectral region. The facility can also be used to obtain EO system performance assessments (scattering coefficients, reflection coefficients, and operational regions of optimal performance) in addition to optical jamming techniques.

This Research Report describes the ECM/ESM Facility and discusses the investigation into the parameters which could modify the radiation incident on the EO systems under test. The parameters comprise effects from the atmosphere, effects from components of the Facility, and effects from the type of radiating source (black body or laser). Detail is given on the atmospheric effects, since any future modification of the Facility to include much longer propagation paths must take these into account.

2 SYSTEM CONFIGURATION

Shown in Figure 1 is the Laser ECM/ESM Facility comprising:

(a) Laser
(b) Steering and focussing optics
(c) Target
(d) Collimator
(e) EO system

The EO system shown in the figure is an IR-seeking missile which is discussed elsewhere (Ref 1).

Operational details of the components listed above are:

2.1 Laser

The Advanced Kinetics He-Xe rare gas laser produces laser radiation containing 10 output lines between 2-4 μm. Table 1 shows a list of observed laser lines. The laser lines either appear simultaneously (using a full reflective cavity mirror) or individually by replacing the mirror with a diffraction grating.

Many of the laser lines can be operated in either a CW mode or modulated mode. Other lines have characteristics which are determined by the temporal behaviour of the gas discharge (population levels) which constrains the lasing lines to a range of modulation shapes. Specific characteristics of these temporal shapes as a function of the discharge parameters are described elsewhere (Ref 2).

2.2 Steering and Focussing Optics

The laser radiation is 'beam steered' onto the focussing optics F, by gold-plated 25 mm diameter mirrors M1, M2 and M3 (Figure 1). The two lenses L1 (diameter 25 mm) and L2 (38 mm) comprise the focussing optics, and condense the laser radiation onto the entrance aperture of the off-axis parabolic collimator PC. The focal length of the lens combination (L1 and L2) have been chosen to match the f/# of the collimator. This ensures that the diameter of the parallel radiation leaving the collimator is comparable to the diameter of the parabolic mirror of PC.

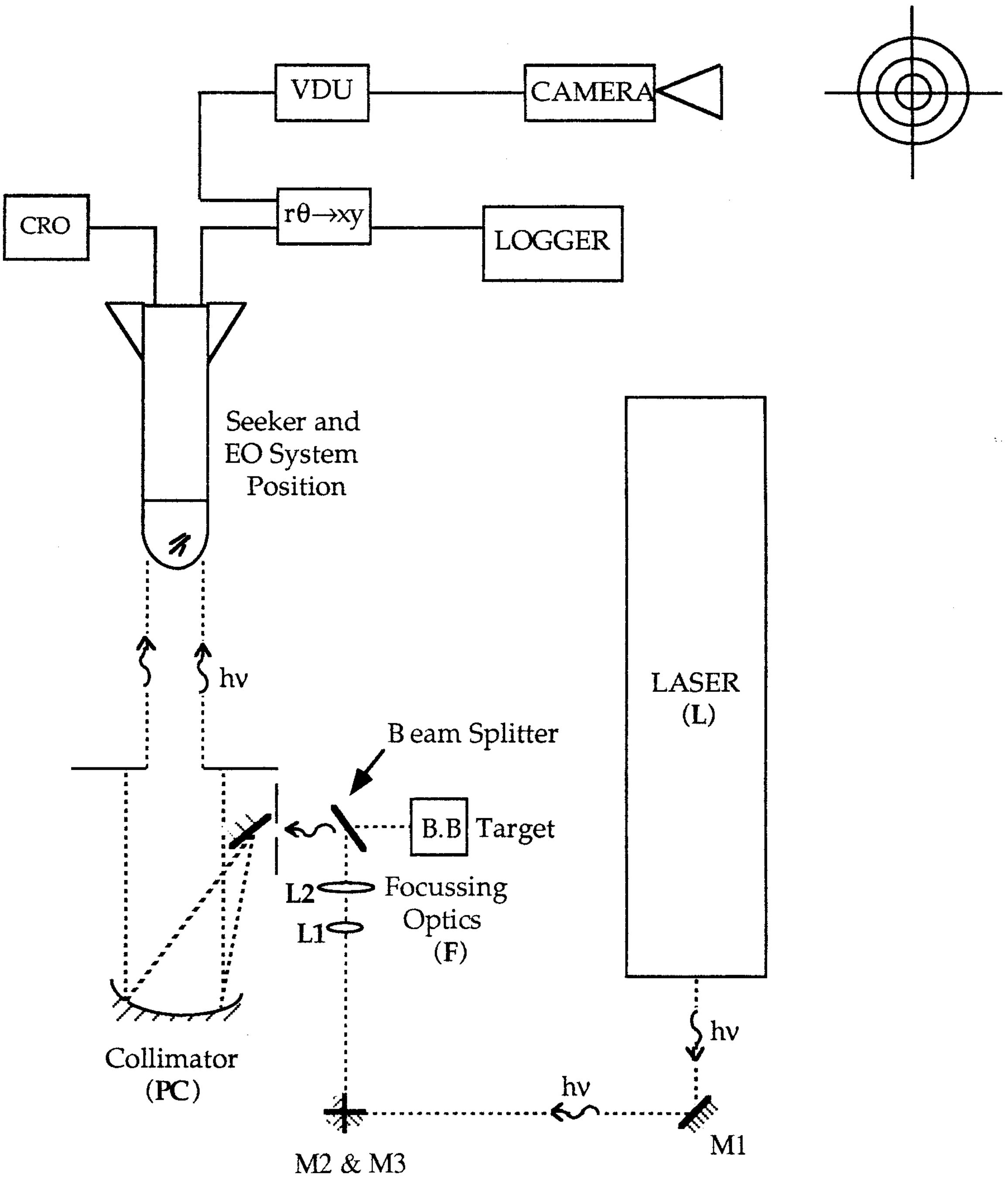


Figure 1 (U) Laser ECM/ESM Facility Configuration

Table 1 He-Xe Laser Lines

Wavelength (μm)	Laser Characteristics	
	Full Reflector	Grating
2.026	Short Pulse	Short Pulse (2nd Order)
2.651	Short Pulse	*
3.366	C.W. and Pulsed	C.W. and Pulsed (≈10 mW)
3.434	C.W. and Pulsed	--------
3.507	C.W. and Pulsed	C.W. and Pulsed (≈25 mW)
3.650	C.W. and Pulsed	Short Pulse
3.679	--------	Short Pulse
3.869	--------	Short Pulse
3.894	--------	C.W. and Pulsed (≈5 mW)
3.995	Short Pulse	Short Pulse

* Using the grating, output at wavelengths below approx. 3.3 μm have not been verified experimentally to date.

2.3 Target

A Barnes Engineering company Black Body (Model 11-210-1) is used as the source object, or target, for the electro-optic system which is to be tested. As shown in Figure 1, laser radiation is combined with the target's radiation using a fused silica beam splitter .

2.4 Collimator

The collimator PC consists of a planar 25 mm^2 rectangular mirror which steers the radiation (target and/or laser) onto a 125 mm diameter parabolic mirror. The collimated radiation (divergence 0.56 m radians, ±3%) is then presented to the EO system under test.

3 SYSTEM EVALUATION

The Laser ECM/ESM Facility has been developed to assess the performance of EO systems and accommodate laser radiation at several orders of magnitude greater than the target radiation. For EO system ESM assessments, the irradiating laser intensity is attenuated to powers comparable to the range used by the EO system in its standard mode of operation. It is therefore necessary to examine any differences that may exist in the collimated radiation between laser and black body radiation, particularly if the EO response to both laser and black body radiation are to be equivalent. The following experiments were performed to investigate any of these differences.

3.1 Irradiance Intensity Range

Irradiance values at the position occupied by the EO System are summarised in Table 2* for both laser and target (black body) sources. Irradiance values have been determined for 1.8 to 2.8 μm waveband and 3.8 to 4.8 μm waveband. Target irradiance values and laser irradiance values can be expressed as a ratio, where:

$$J/S = \frac{\text{Laser irradiance within the spectral bandpass of the EO system}}{\text{Target irradiance within the spectral bandpass of the EO system}}$$

As shown in Table 2, J/S values of three orders of magnitude are obtainable within the 3.8-4.8 μm waveband. (Note the different units for black body and laser irradiances.)

Table 2 Irradiance Intensity Ranges.

EO Pass Band (μm)	Black Body Temperature		Laser Wavelength (μm)		
	200°C	1000°C	2.026	3.507	3.894
	(nW/cm^2)		($\mu W/cm^2$)		
1.5 - 5.0	1.36	370	2.2	100	20
1.8 - 2.8	0.04	140	2.2	---	---
3.8 - 4.8	0.77	70	---	---	20

3.2 Variations In The Focal Plane

Intensity variations across the plane perpendicular to the collimated radiation from PC can show as significant spatial intensity variations in the image or Fourier plane (Ref 3). To assess the magnitude of this effect, an AGA Thermovision imager was used as the EO System under test (see Figure 1). The effects of laser irrradiance and black body irradiance were consecutively recorded. The images obtained were less than the spatial resolution of the imager, indicating that there is no significant observable spatial difference in the Fourier plane, between the laser or black body.

3.3 Atmospheric Effects

The magnitude of the effect of atmospheric turbulence (intensity scintillation, beam wander, temporal profile variation) within the Laser ECM/ESM Facility was experimentally assessed by recording the temporal response from the AGA image and determining the magnitude of the frequency components comprising each temporal signal.

* Calculations of values in Table 2 are shown in Appendix II.

The collimator PC expands the laser beam width by 16 times. The AGA image of the beam profile obtained by imaging the diffuse laser radiation off a lambertian surface, is therefore just discernible from the ambient background. Since the laser radiation is focussed onto an aperture, as described in section 2.2, the atmospheric effects over path lengths comparable to the ECM/ESM Facility, must be evaluated. Since the ratio of the laser to ambient background irradiance has to be larger than 'just discernible', a side experiment was performed to check the effect of passing laser radiation through a focus, prior to collimation. Using a positive lens and then a negative lens, a diffusing screen was placed several centimetres in front of the focal plane, to enable the diverging radiation to diffusely reflect off a lambertian surface and be recorded by the AGA (see Figure 2). Using this method, an image was recorded which had good contrast with the ambient background, and extended over a significant portion of the AGA's field of view. Figures. 3(a) and 3(b) show images of the lambertian surface using positive and negative lenses, respectively.

3.3.1 Image to Frequency Conversion

The AGA image is derived from the temporal detector voltage. This voltage is proportional to the modified irradiance at the detector surface*. An AGA Sampling System was used to sample and then hold the temporal voltage signal at a pre-selected point on the video-line. On play-back of a recorded image, the temporal voltage, and hence, temporal irradiance of a chosen point on the image can be recorded. An XT-compatible computer was used to store such temporal signals after they had been digitised by a PC-Labcard (model PCL-718) A/D Board. A Fast Fourier Transform was performed on each temporal record to extract the frequency components. Figs. 4(a) and 4(b) show the a.c. frequency components constituting records from the positive and negative lens, respectively. The two lenses gave similar results indicating that the magnitude of the temporal-atmospheric effects are less than the resolution of the AGA (200 μm).

3.4 Statistical Calculations for the ECM/ESM Facility

As discussed in Appendix I, the magnitude of intensity scintillations determines the type of atmospheric turbulence which is applicable to the optical path under consideration. The variance of the log amplitude fluctuation is given by Equation I.1 :

$$\delta^2 = 0.307 C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}}$$

where C_n is the refractive index parameter,

$k = 2\pi/\lambda$,

and L is the propagation path length.

For a 6 mm diameter laser beam with an output wavelength at 4 μm and a propagation path length of 3 m, then:

$$\delta^2 = 3.89 \times 10^{-5}$$

* The modified irradiance is that obtained from integrating the product between the incident spectral irradiance and the spectral response function of the detector, over the waveband of detection.

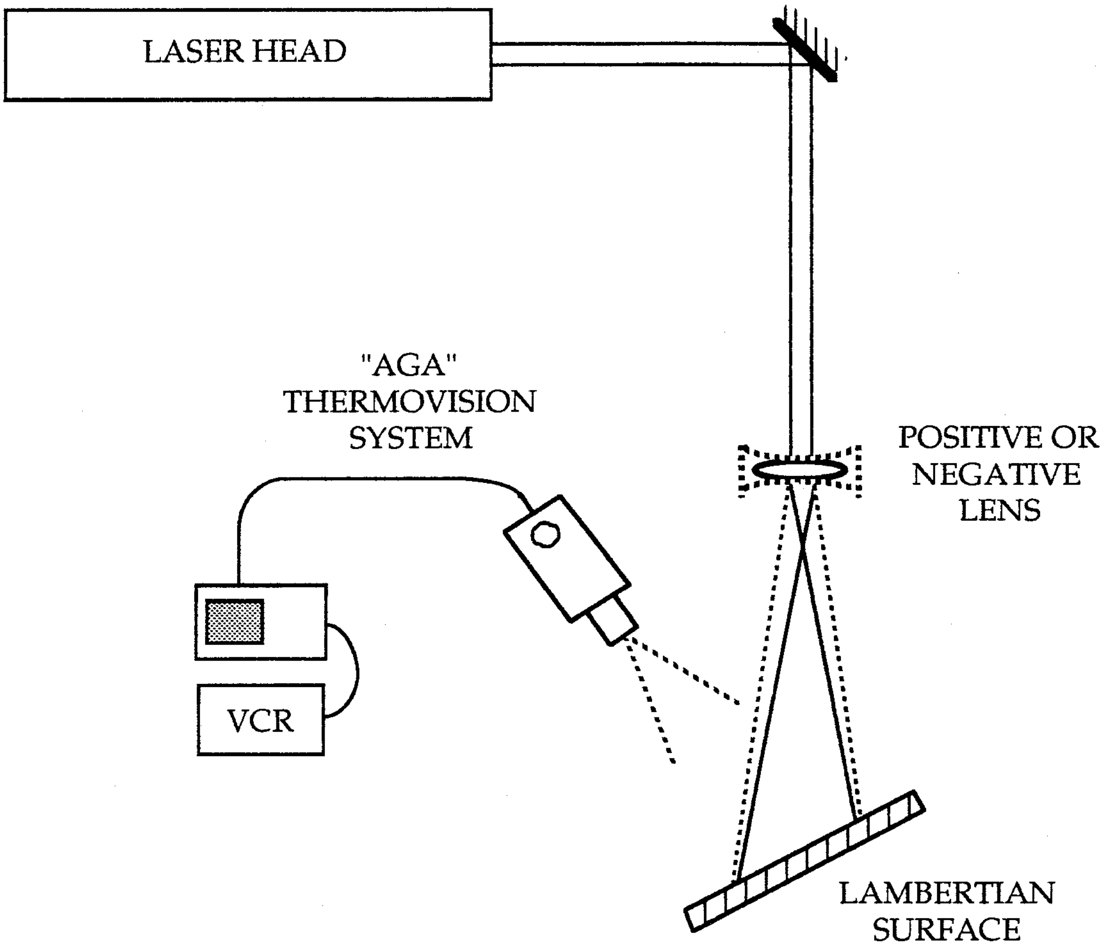
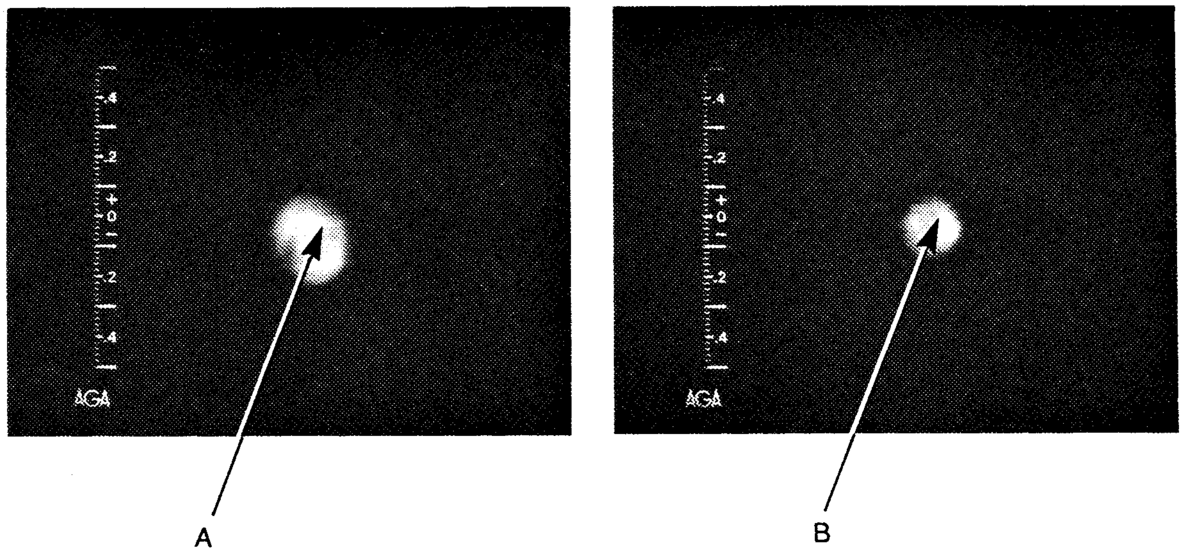
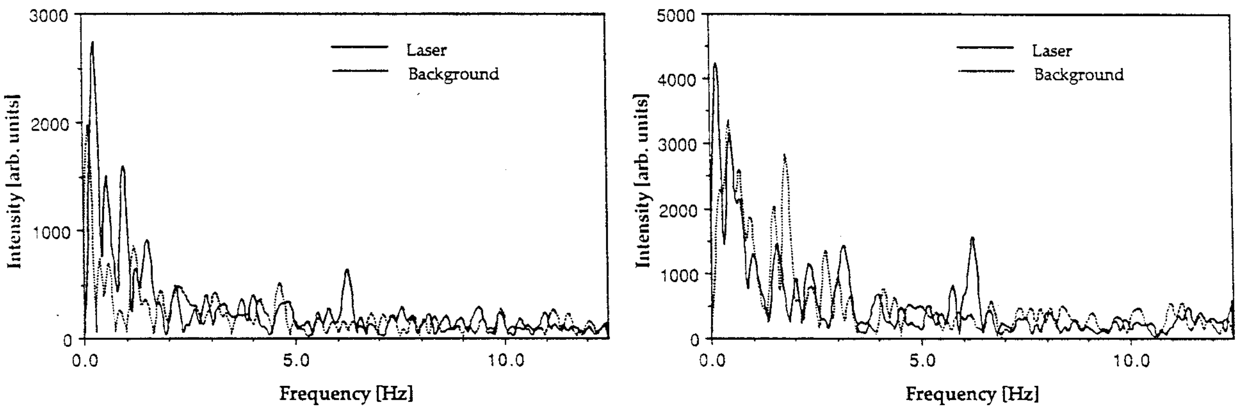


Figure 2 Schematic of positive and negative lens configurations to obtain beam profile images



(a) (b)

Figure 3 Beam profile images obtained from the inserted lambertian surface for (a) positive lens and (b) negative lens. Points A and B represent spatial points where an FFT was performed on the temporal signal (see Figure 4).



(a) (b)

Figure 4 FFT records of (a) positive lens and (b) negative lens

Since δ^2 << 0.2 then weak turbulence is applicable and a value for the Displacement Variance (derived from the Rytov solution to the scalar wave equation in Appendix I) can be calculated. The equation for the Standard Displacement Deviation is given by:

$$\sigma_1 = 0.98 C_n D^{-\frac{1}{6}} L^{\frac{3}{2}}$$

$$\sigma_2 = 1.05 C_n D^{-\frac{1}{6}} L^{\frac{3}{2}}$$

where the subscripts 1, 2 denote a collimated and focussed beam respectively.

C_n is the refractive index parameter

D is the beam diameter

L is the propagation path length

Thus, for a 6 mm diameter laser beam at 4 mm and a propagation length of 3 m and using the maximum value in the C_n range of 10^{-6} $m^{-1/3}$ then:

$$\sigma_1 = 2.17 \times 10^{-6} \mathrm{m}$$

and

$$\sigma_2 = 2.33 \times 10^{-6} \mathrm{m}$$

which implies that the beam wander by 4 standard deviations (94% of observed values) will be deviated by less than 9.3 μm. In section 3.3.1, the frequency components which occur on all the FFT records other than the ambient background record, are believed to be associated with the AGA imager since both the calculated variance of the log amplitude fluctuation and displacement variance predict values at least an order of magnitude less than the observed values.

4 CONCLUSIONS

The laser ECM/ESM facility has been built to determine aspects of electro-optic system performance in conjunction with laser electronic countermeasure techniques. Extensive evaluations of atmospheric effects within the system have been determined to ensure that the irradiation of any electro-optics placed within the system is free from either atmospheric (other than attenuation due to absorption) or system-configuration influences. This has been demonstrated for a 50 mW laser operating between 2 to 4 μm and path lengths less than 10 m. Attainable maximum J/S values are in the region of three orders of magnitude. Future modifications to the Facility will include the incorporation of a high repetition-rate, high peak power pulsed laser (>1 kHz) to investigate the effects of pulse train modulation on EO systems.

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APPENDIX I

ATMOSPHERIC TURBULENCE

As a beam of radiation propagates through the atmosphere it is subjected to random deflections due to refractive turbulence. This results in a beam, at the point of observation which, depending upon the atmospheric parameters and propagation length, varies temporally in intensity, is displaced within the plane transverse to the direction of propagation, and can contain regions of high intensity across the otherwise defined beam profile. Although the refractive index variation from the mean value is very small, a propagation through a large number of refractive index inhomogeneities can result in a significant cumulative effect.

Even though propagation distances within the ECM/ESM Facility are relatively short (~3 m), it was necessary to determine the magnitude of the atmospheric effects within the system.

Because the refractive index fluctuations can be viewed as purely a statistical property, then in the classical theory of wave propagation, simplifications can be made to the scalar wave equation (Ref. 4)

$$\{\nabla^2 + k^2[1 + 2n(\bar{r},t)]\}U(\bar{r},t) = 0$$

such that a value for the beam intensity variance and displacement variance can be determined. Using the solution of Rytov (Ref. 4) the variance of the log amplitude fluctuation or scintillation can be expressed as:

$$\delta^2 = 0.307 C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}} \qquad \text{I.1}$$

Provided $\delta^2 < 0.2$ then the atmospheric turbulence is considered weak and the propagated beam preserves its size. If on the other hand $\delta^2 > 0.5$ then strong turbulence occurs, and the beam will fragment into subregions of higher intensity. In this situation a rigourous solution to the wave equation must be sought.

In conditions of weak turbulence, beam wander or Variance of Displacement is given by (Ref. 5):

$$\sigma^2 = 0.97 C_n^2 D^{-\frac{1}{3}} L^3 \, {}_2F_1\left(\tfrac{1}{3};1;4;\tfrac{L}{f}\right) \qquad \text{I.2}$$

where D is the beam diameter

L is the propagation length

f is the focal length of the converging beam (As $f \to \infty$ the beam becomes collimated)

${}_2F_1$ is the hypogeometric function

C_n is the refractive index parameter (Ref. 6) and is typically in the range

$$10^{-17} m^{-\frac{2}{3}} < C_n^2 < 10^{-12} m^{-\frac{2}{3}}$$

For a collimated beam (L/f=0), Equation I.2 reduces to The Standard Deviation:

$$\sigma_1 = 0.98 C_n D^{-\frac{1}{6}} L^{\frac{3}{2}}$$

and for a focussed beam (L/f=1):

$$\sigma_2 = 1.04 C_n D^{-\frac{1}{6}} L^{\frac{3}{2}}$$

APPENDIX II

IRRADIANCE CALCULATIONS

II.1 Black Body Irradiance Calculations

To calculate the irradiance at the surface of the EO System as shown in fig 1 of the main text, the irradiance of the aperture of the Collimator (PC) from the target must be calculated. Since the diameter of the radiating black body is comparable to the separation between it and the aperture, as shown in fig II.1, the irradiance of the aperture is given by

$$H(\lambda) = \int_A \frac{\tau(\lambda)N(\lambda)\cos^2\theta}{R^2}\,dA \qquad \text{II.1}$$

where $N(\lambda)$ is the spectral radiance given by

$$N(\lambda) = \frac{W(\lambda)}{\pi}$$

where

$$W(\lambda) = \frac{C_1}{\lambda^5}\frac{1}{e^{C_2/\lambda T} - 1}$$

and C_1, and C_2 are the black body radiation constants given by

$C_1 = 3.7418 \times 10^4$ W.cm^{-2}.µm^4

and $C_2 = 1.43879 \times 10^4$ µm.K

$\tau(\lambda)$ is the spectral atmospheric transmittance,

R is the range between the radiating black body element dA and the aperture.

Since the purpose of calculating the Irradiance at the EO system surface is to compare the magnitude with that of the laser irradiance, then Equation II.1 is approximated by

$$H(\lambda) = \tau(\lambda)N(\lambda)\int_A \frac{\cos^2\theta}{R^2}\,dA \qquad \text{II.2}$$

and $\tau(\lambda)$ is evaluated over the path length L in fig II.1

Equation II.2 reduces to

$$H(\lambda) = \tau(\lambda)N(\lambda)\pi\sin^2\phi \qquad \text{II.3}$$

where ϕ is the angle between L and the maximum distance for which radiation originates from the black body, is incident on the aperture and is collimated by PC. Note that this does not necessarily occur at the circumference of the black body, but rather the circumference of the solid angle cross section defined by the f/# of the collimator as shown in Figure II.2.

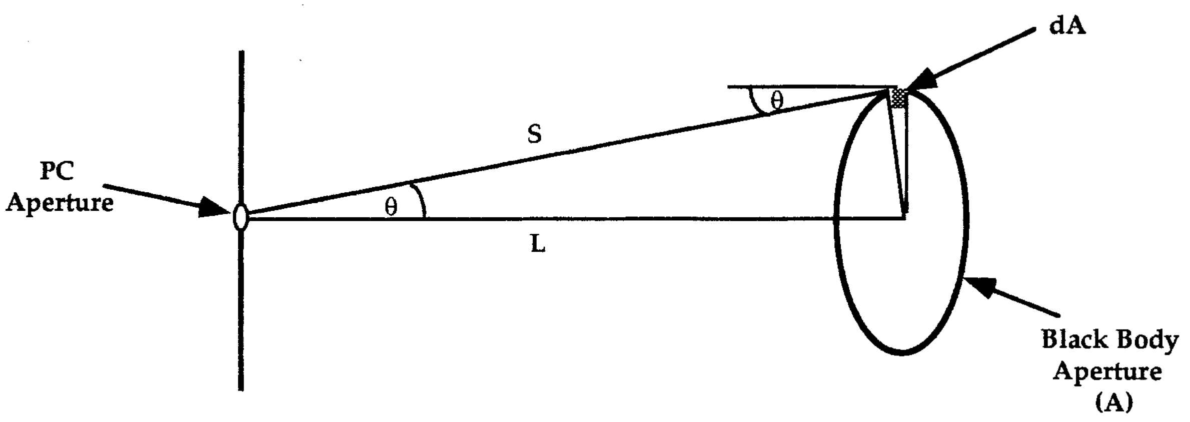

Figure II.1 Geometric Evaluation of Extended Black Body Irradiating Aperture of Collimator PC.

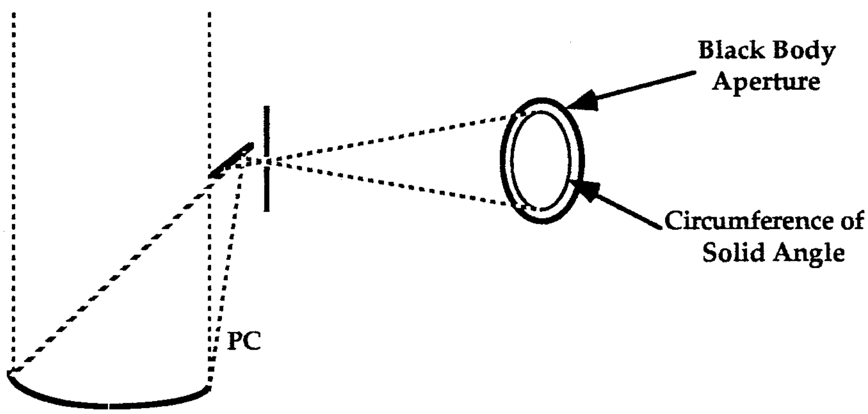

Figure II.2 Geometric Configuration for Solid Angle Evaluation.

The total irradiance at the EO System surface and within the passband of the EO System, is given by

$$H = G\int_{\lambda_1}^{\lambda_2} \tau'(\lambda) H(\lambda) \varepsilon(\lambda)\, d\lambda \qquad \text{II.4}$$

where $H(\lambda)$ is obtained from II.3, $\tau'(\lambda)$ is the spectral atmospheric transmittance over the propagation path,$\varepsilon(\lambda)$ is the spectral transmittance value for the beamsplitter, and G is the factor ratio of optical expansion. It is given by

$$G = \frac{\text{Area of Aperture}}{\text{Final Irradiating Area}}$$

II.1.1 Numerical Calculation

Atmospheric transmittance values $\tau'(\lambda)$ were obtained by running the Lowtran 6 program on an XT-compatible computer over a path length of 2 metres. ϕ in Equation II.3 was evaluated to be 5.45°. $N(\lambda)$ was obtained for a 200°C and 1000°C black body. The factor ratio G of 8.53×10^{-6} was evaluated, and $\varepsilon(\lambda)$ was given as 0.5. Integration in Equation II.4 was performed by the rectangular method. Although this method produces maximum errors, it served the purpose of irradiance magnitude comparisons.

II.2 Laser Irradiance Calculation

To calculate the irradiance at the EO systems surface due to the laser, the following technique was used. Given the final irradiating area A, the atmospheric transmittance $\tau(\lambda)$ at the laser wavelength and over the axial path length, and the power P, then the irradiance is given by

$$H(\lambda) = \frac{P\,\tau(\lambda)\varepsilon(\lambda)}{A}$$

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17 SUMMARY OR ABSTRACT
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